B. 6 Ventilation-perfusion inequalities

a. Describe West's zones of the lung and explain the mechanisms responsible for them.

Perfusion of the lung is not uniform in the erect position, but increases from the top to the bottom of the lung. This is a result of hydrostatic forces combined with the effect of airway pressure. Conceptually, the lung may be divided into three zones.

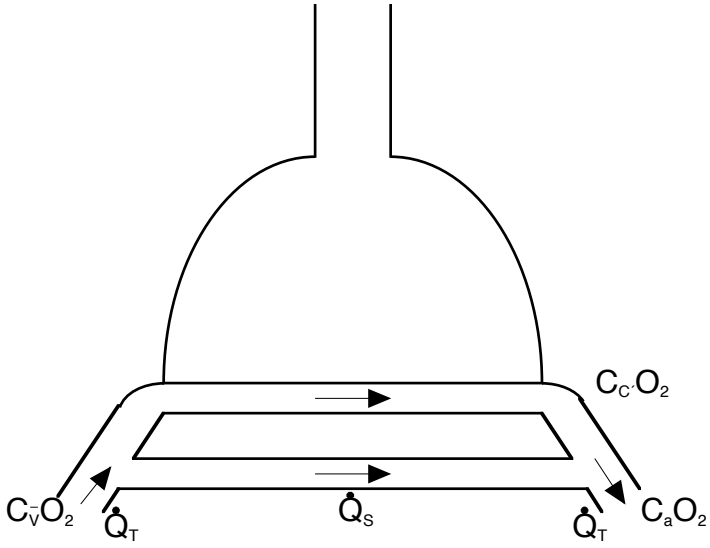
Zone 1 is a region at the top of the lung in which arterial pressure falls below alveolar pressure. This does not happen under normal circumstances, but can result from marked hypotension or from raised alveolar pressure in IPPV. The capillaries in this zone remain collapsed and no perfusion occurs.

Zone 2 is the region of lung where pulmonary arterial pressure is greater than alveolar pressure but venous pressure remains below alveolar pressure. Here perfusion is dependent on the gradient from arterial pressure to alveolar pressure as vessels collapse at the point where intravascular pressure has fallen below alveolar pressure, limiting flow. Pulmonary venous pressure has no influence on flow, but perfusion increases from top to bottom of zone 2 as arterial pressure rises further above alveolar pressure.

Zone 3 is where both arterial and venous pressure exceeds alveolar pressure. Now airway pressure does not influence perfusion as flow is dependent on the arterial-venous gradient. Flow increases in moving down zone 3 because the mean volume of the vessels does, as both arterial and venous pressure rise, distending the capillary bed. The pressure gradient remains the same.

A so-called zone 4 arises in areas of lung where low lung volume reduces the size of extra-alveolar vessels, increasing their resistance and reducing blood flow. This can be seen at the lung bases at low lung volumes.

b. Explain the shunt equation.



Part of the difference between mixed P_aO_2 and P_AO_2 is conceptualized as being due to "shunted" blood which circulates through the lung without being exposed to the blood-gas barrier. Part of the "shunt" blood is certainly that in the bronchial circulation and blood perfusing alveoli which are not ventilated, but the calculated value for shunted blood flow includes both anatomically shunted blood and a proportion of blood from inadequately ventilated alveoli where P_AO_2 is lower than the ideal value.

Because the total volume of oxygen carried in the pulmonary venous blood is conserved in the mixing of shunted and ventilated blood, and the alveolar and systemic venous oxygen concentrations can be measured, it is possible to calculate the proportion of pulmonary perfusion which is represented by shunted blood:

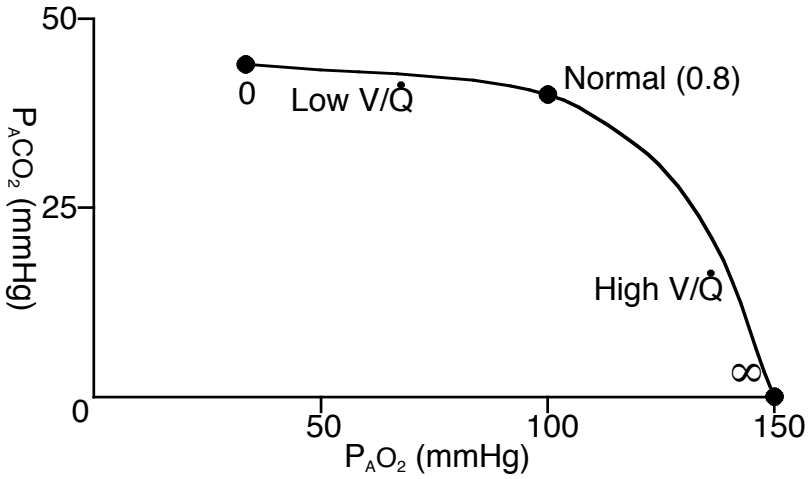
$$\dot{Q}_T \cdot C_aO_2 = \dot{Q}_S \cdot C_{\bar{v}}O_2 + (\dot{Q}_T - \dot{Q}_S) \cdot C_{C'}O_2$$

which can be rearranged to give:

$$\frac{\dot{Q}_S}{\dot{Q}_T} = \frac{C_{C'}O_2 - C_aO_2}{C_{C'}O_2 - C_{\bar{v}}O_2}$$

If the end-capillary blood is assumed to have equilibrated with alveolar oxygen, its oxygen concentration can be determined from the oxygen dissociation curve. The arterial and mixed venous oxygen concentrations can be measured directly, allowing for calculation of the shunt flow.

c. Describe the oxygen-carbon dioxide diagram and apply it to clinical use.



The oxygen-carbon dioxide diagram relates PCO_2 and PO_2 in the alveolus to V/Q ratio. With a V/Q ratio close to 1, PCO_2 has its normal value of around 40 mmHg and PO_2 100 mmHg. As V/Q ratio increases, the gas partial pressures approach those of inspired gas. This is the situation in functional dead space.

As V/Q ratio falls, the gas partial pressures approach those of mixed systemic venous blood; the situation of shunt. Thus the curve always runs from the values of venous blood to those of inspired gas, whatever their compositions. The composition of alveolar gas must always lie on the curve: there is a 1-1 correspondence of values for PCO_2 and PO_2.

In a normal lung there is a spread of V/Q ratios among the alveoli, causing some alveoli (with high V/Q) to return blood with a gas composition closer to inspired gas and some (with low V/Q) to return blood which is more similar to mixed venous blood.. With disease this spread gets much wider, causing a rise in PCO_2 and a fall in PO_2.

The normal physiological response to a fall in PCO_2, is a rise in respiratory rate and volume. This increases the ventilation of all alveoli and shifts the distribution of V/Q ratios towards the higher end of the curve. As is clear from the curve, with increasing ventilation the PCO_2 of some units approaches 0, while the PO_2 (on air) approaches only 1.5 times normal. As a result, an increase in ventilation is much better at normalizing PCO_2 than PO_2. This problem can also be seen in the oxygen and carbon dioxide dissociation curves; the oxygen curve is quite flat with above normal ventilation while the carbon dioxide curve remains almost linear.

d. Describe and explain regional ventilation-perfusion inequalities, their clinical importance and changes with posture.

In the upright position, V/Q ratio decreases from top to bottom of the lung. This is caused by the variation in both ventilation and perfusion resulting from pressure differences from top to bottom of the lung. Ventilation is greater at the base due to the lower mean volume at rest and thus greater compliance at the base of the lung. Perfusion is also greater at the base of the lung due to hydrostatic pressure increasing both arterial and venous pressure. The increase in perfusion at the base is greater than that in ventilation, hence the fall in V/Q.

	Apex	Base	
ventilation	0.24	0.82	l/min
perfusion	0.07	1.29	l/min
V/Q	3.3	0.63	
PO_2	132	89	mmHg
PCO_2	28	42	mmHg
pH	7.51	7.39	

The normal V/Q scatter is responsible for a proportion of the A-a gradient. There is a greater blood flow from the base of the lung where the PO_2 is low and relatively less from the apex. The small rise in oxygen content of blood flow from the apex cannot

compensate for the larger flow from the base and so the mean P_{O_2} is depressed. This effect is exacerbated by the shape of the oxygen dissociation curve which is steeper below ideal P_{O_2} than above.

With a change to the supine position, the range of V/Q scatter is reduced because the vertical dimension of the lungs is reduced. There is a reduction in physiological dead space.

In the lateral position, the same gradient of ventilation and perfusion occurs as in the upright position, except that it extends from the superior to inferior lung. With the introduction of IPPV in the lateral position, the dependent lung is no longer much better ventilated than the upper lung, presumably due to the reduced compliance of the compressed side of the chest. Detail in Thoracic surgery.

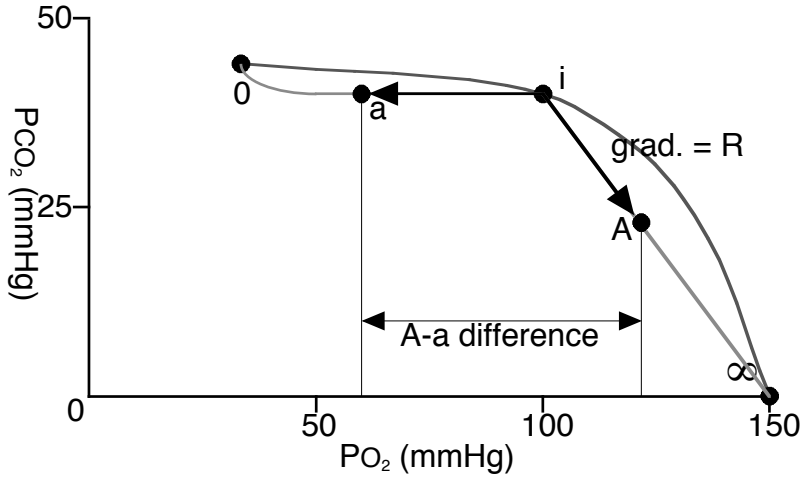
e. Outline the methods used to measure ventilation-perfusion inequalities.

To detect regional defects in ventilation or perfusion, radiolabelled tracer is used in conjunction with a gamma camera. A perfusion scan is performed using radiolabelled (Tc99m) dye. The corresponding ventilation scan uses a low concentration of radioactive gas (Xe). The images obtained show gross areas of defective perfusion or ventilation and allow differentiation between large isolated perfusion defects such as pulmonary emboli and matched defects such as pneumonia.

Physiological uniformity of ventilation can be assessed using a single- or multiple-breath N_2 washout test. The single-breath method shows a rise in N_2 concentration at the end of the alveolar plateau as inadequately ventilated alveoli are emptied. The change in N_2 concentration between 750 ml and 1250 ml expired volume is used as an indicator of uneven ventilation.

The multiple-breath method relies on the exponential washout of N_2 over multiple breaths containing no N_2. In a perfectly ventilated lung this would result in a straight line on a semi-log plot of N_2 concentration versus breath number. Where alveoli with large time-constants delay the washout of N_2, the curve becomes curved (concave-up). This can be quantified by modelling the shape of the curve using more than one "compartment".

An assessment of the V/Q distribution can also be made from the P_{O_2} difference between ideal alveolar gas and arterial blood. Real alveolar gas P_{O_2} is difficult to measure unless there is completely even ventilation.



As V/Q scatter widens, the difference between the composition of alveolar gas and arterial blood widens, diverging from the point of ideal matching (i). The alveolar gas composition (A) falls on the line of gradient R, connecting i with the composition of inspired gas. The arterial gas pressures (a) follow a line to the mixed venous composition, with P_{CO_2} initially held constant by the ventilatory response to any rise in P_{CO_2}. The point a can be measured directly with blood gases and the point A calculated from the alveolar gas equation.

Other measures of V/Q inequality include *physiological shunt* and *alveolar dead space*. These are measures of the amount of venous blood or inspired gas added to produce the measured alveolar or arterial composition from the ideal composition:

$$\frac{\dot{Q}_{PS}}{\dot{Q}_T} = \frac{C_iO_2 - C_aO_2}{C_iO_2 - C_{\bar{v}}O_2}$$

$$\frac{V_{Dalv}}{V_T} = \frac{P_iCO_2 - P_ACO_2}{P_iCO_2}$$

Alveolar dead space is difficult to calculate because of the difficulty of measuring alveolar PCO_2, so mixed expired PCO_2 and arterial PCO_2 (to approximate ideal PCO_2) are used instead, giving *physiological dead space*.

$$\frac{V_{Dphys}}{V_T} = \frac{P_aCO_2 - P_ECO_2}{P_aCO_2}$$

f. Explain venous admixture and explain its relationship to shunt.

Venous admixture is a conceptual quantity, being the amount of mixed venous blood which would have to be added to ideal pulmonary capillary blood to produce the measured gas composition of arterial blood. In a lung where V/Q matching was perfect, it would equal the amount of shunted blood. It is also called *physiological shunt* and is a measure of the degree of V/Q mismatch. The equation for its calculation is given above.

g. Explain the clinical significance of changes in anatomical and physiological dead space.

Anatomical dead space is the volume of the conducting airways. It may be measured most commonly using an N_2 washout test or by making a cast of the airways in a cadaver or using the Bohr equation using end expiratory CO_2 and mixed expired CO_2 in the same manner as the N_2 washout test:

$$\frac{V_{Danat}}{V_T} = \frac{P_{ET}CO_2 - P_ECO_2}{P_{ET}CO_2}$$

Physiological dead space is the volume of airways which do not participate in CO_2 exchange and is determined from the Bohr Equation as given above. The two values are very similar in a healthy individual.

Anatomical dead space represents the difference between total ventilation and gas available for alveolar ventilation. It is typically about 150 ml and is decreased with intubation by the volume of the larynx and pharynx bypassed by the ETT or LMA. The addition of a circuit introduces *apparatus dead space* which is the volume of the circuit beyond the Y-piece in a circle system.

An increase in anatomical dead space increases the mean inspired CO_2 and reduces the mean inspired O_2, as the first gas inspired will be of end-tidal composition. This results in an increase in minute ventilation in response to the rise in PCO_2 in a spontaneously ventilating patient. The rise in anatomical dead space required to produce significant compromise is large.

Small increases in anatomical dead space are seen with changes in posture: the erect position increasing dead space by about 50 ml over the supine position and neck extension increasing volume of the pharynx another 25 ml. Small increases are also seen with bronchodilation and with deep inspiration.

Physiological dead space increases both with an increase in volume of the conducting airways and with any increase in alveolar dead space. Alveolar dead space may increase as a result of V/Q mismatch: non-perfused alveoli, poorly perfused alveoli and non-vascular air space (in emphysema).

h. Explain the effect of ventilation-perfusion inequality on carbon dioxide elimination and oxygen transfer.

Increased V/Q mismatch impairs both CO_2 and O_2 transfer, but to different degrees. Oxygen uptake is more markedly affected because of the shape of the oxygen uptake curve. Alveoli with a low V/Q and consequently lower PO_2 cause a substantial fall in the oxygen concentration of blood leaving poorly ventilated alveoli, but alveoli with a high

V/Q and high PO_2, produce only a small rise in oxygen concentration. If mixed venous blood contains 14.6 ml/100 ml O_2, a normal alveolus (V/Q = 1) will raise this to 19.5. A V/Q ratio of 0.1 will result in a rise to only 16 and a ratio of 10 will produce an oxygen concentration of only 20 ml/100 ml.

CO_2 elimination is less affected by V/Q mismatch. This is partly due to the more linear relationship between PCO_2 and CO_2 concentration and mostly due to the importance of $PaCO_2$ in determining ventilatory drive. Any rise in $PaCO_2$ resulting from V/Q mismatch will result in an increase in ventilation to normalize $PaCO_2$. A rise in total ventilation is effective in increasing the elimination of CO_2 from both well- and poorly-ventilated alveoli, so $PaCO_2$ is easily normalized.